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HIGH PRESSURE WORKING MODE OF HOLLOW
CATHODE ARC DISCHARGES

H. Minoo and C. Popovici

Translation of "Fonctionnement a Haute Pression
des Decharges d'Arc a Cathode Creuse", Paris-Sud
University. Orsay (France) Lab. de Physique des
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SUMMARY

The operation of high-pressure cathotrons is subjected to systematic study. The cathotrons are hollow gas-flow cathodes equipped with an additional heating system which preheats either the gas injected by the cathode or the cathode itself. In this study the influence of various parameters of the arc on the behavior of the cathotrons is analyzed. Three specially suitable configurations (cathotrons I, II, and III) are proposed.

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1

HIGH PRESSURE WORKING MODE OF HOLLOW-CATHODE ARC DISCHARGES

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1 - INTRODUCTION

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In discharge tubes the passing of current between the solid phase (electrode) and the gaseous phase is always accompanied with more or less rapid deterioration of the electrode. This deterioration is generally more pronounced in the region of the cathode. It increases with the current of the discharge, and with a sufficiently high current (usually when an arc is produced) it is so intense that

* Numbers in margin indicate foreign pagination

the life of the electrode (and more particularly the cathode) is severely reduced.

In order to limit deterioration of the electrode to acceptable proportions, the density of the current would have to be diminished in the transitional solid/gas zone, which, in other words, means that the dimensions of the zone would have to be enlarged.

a) Single-Channel Hollow Cathode

One possible solution to the problem consists in using hollow gas-flow cathodes having a single channel. Such cathodes, which have been under study for several years [1] [2], have the two following special characteristics:

- The cathode is in the shape of a cavity;
- A longitudinal pressure gradient is maintained in the cavity by injection of the gas at the inlet and rapid pumping at the outlet (cf. Fig. 1A).

During normal operation of the arc, a brighter and hotter region appears on the cathode tube. Pyrometric temperature measurements of the external surface of the cathode indicate that the curve of longitudinal temperature distribution reaches a maximum (cf. Fig. 1B). This zone of maximum temperature which usually plays the role of cathodic spots, but which is diffused in this type of discharge, is called the "active zone". It delimits the section of

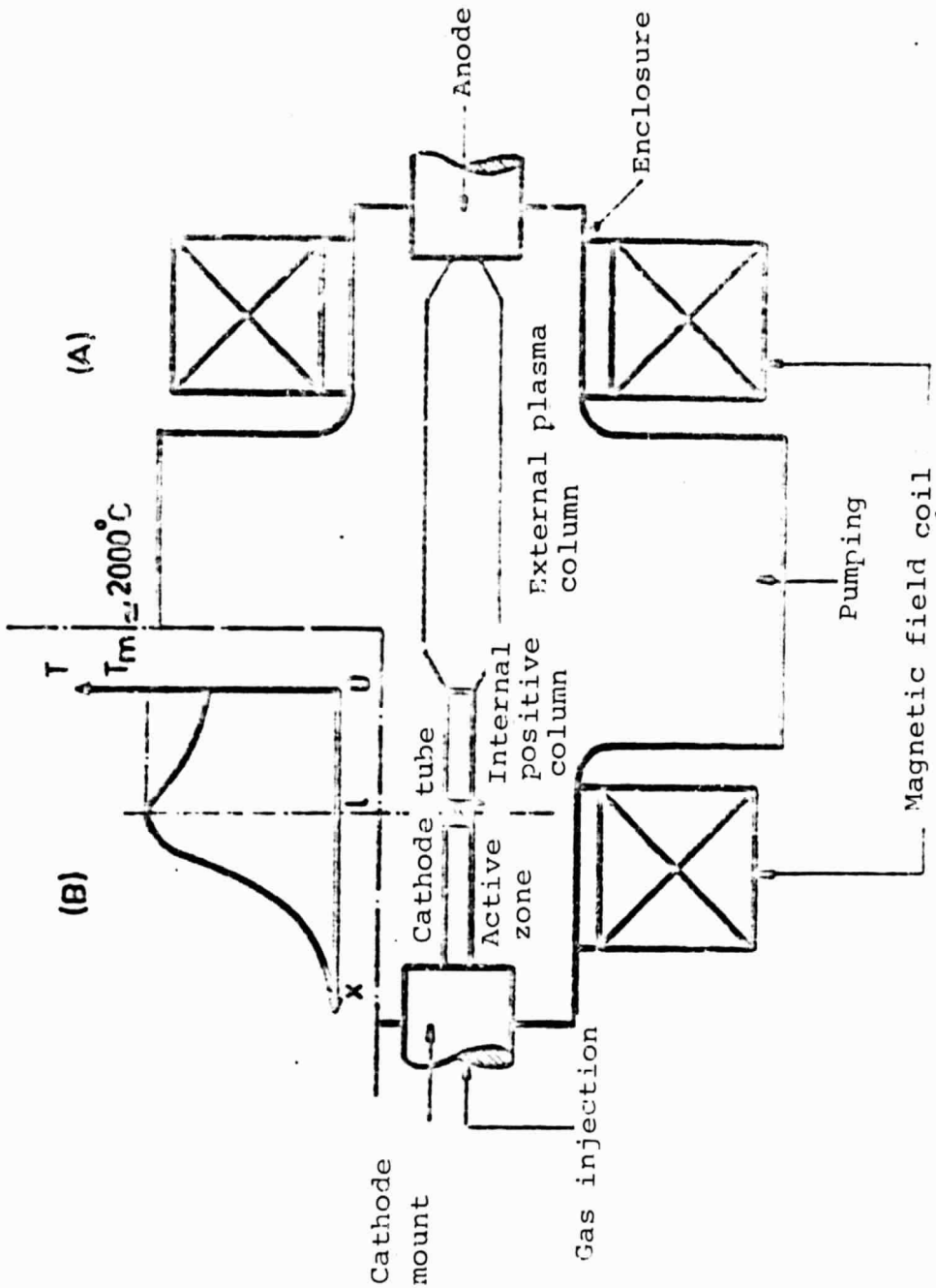


Fig. 1 - Basic diagram and the different regions of the hollow cathode arc discharge.

the cathode, where the current passes preferentially between the solid phase and the gaseous phase of the /3 discharge.

During normal operation, the cathode reaches a maximum temperature of about 2000°C . Since this temperature level is lower than in the cathodic spots of traditional discharge arcs, the amount of vapor released is much less than in the case of the latter and the life of the electrode and the purity of the plasma jet are therefore improved. Also the absence of a localized spot makes the plasma more stable.

These advantages are especially desirable in applications requiring very intense currents along with a reasonable service life of the electrodes - a "clean", dense, highly ionized and quiet plasma (stable plasma).

(b) Multiple-Channel Hollow Cathode

In order to improve performance of the cathodes, we built and perfected hollow electrodes with several channels (cf. Fig. 2), [2,3].

These electrodes enabled the active zone to be enlarged, the service life of the cathode to be increased, and the voltage V of the discharge to be decreased.

As a general rule, optimum operation of these two types of electrodes (single channel and multiple channel) is only satisfactory at low pressures ($p < 1$ torr) [2]. It is noticed during experimentation that as the pressure is increased the dimensions of the active zone decrease, its temperature rises and the zone shifts toward the cathode outlet. Thus, with pressures of 1 torr or more the cathode is subjected to excessive thermal activity which reduces the life of the cathode and favors the transformation of the discharge from a hollow cathode arc into a classical arc.

The analysis of the energy balance in the cathodic region which follows indicates that thermal effects are the cause of shrinking of the active zone. A simple solution to this problem consists in compensating for thermal losses by additional heating of the gas injected by the cathode and of the cathode itself [2]. This solution gave birth to a new type of electrode

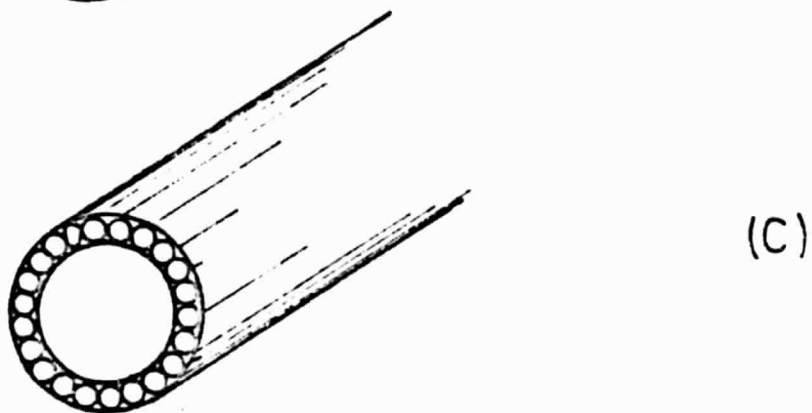
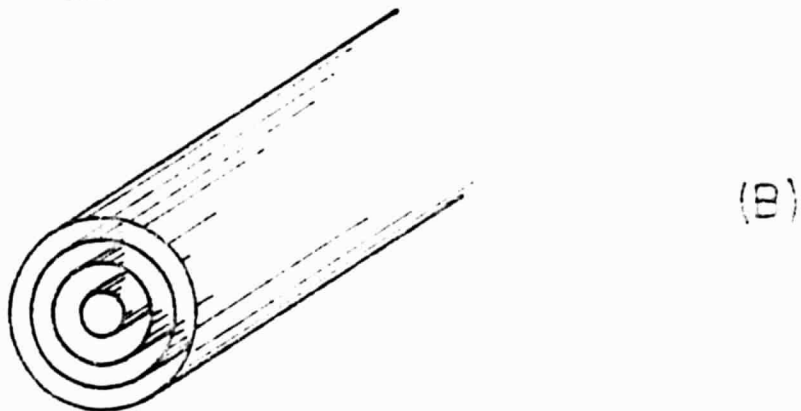
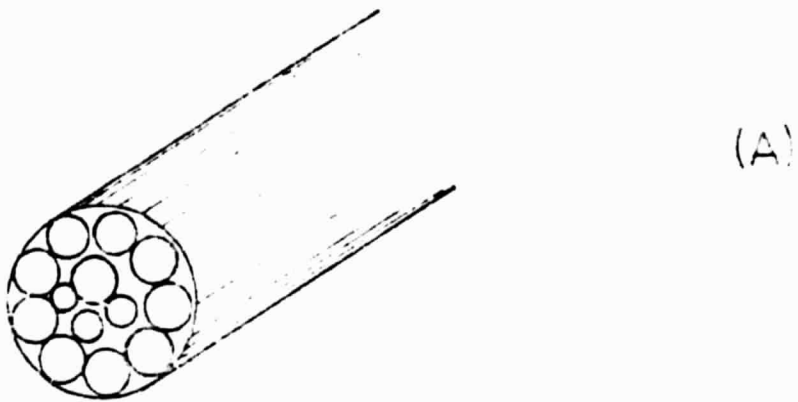


Fig. 2 - Multiple-channel hollow cathodes.

which we have designated as "Cathotrons" because the device is similar to plasmotrons but operates with hollow heated cathodes.

2 - ENERGY BALANCE IN THE CATHODIC REGION

The temperature of the cathodic surface is the result of an equilibrium between the energy gains and losses in the cathodic region. We will now briefly detail and analyze them in the case of a cylindrical cathode with a single channel:

a) Gains: The surface of the cathode is heated by the flow of current in that region. It is subjected to intense bombardment of ions, excited atoms, of radiation emitted by the plasma, and possibly with rapid neutral particles created by charge transfer from the ions. The overall energy created in the cathodic region is equal to:

$$G = I (V - \varphi) \quad (1)$$

where I is the total current of the discharge, V the potential drop in the cathodic region and φ the material output work of the cathode.

b) Losses: The energy created in the cathodic region is evacuated by the following processes:

1) Radiation from the incandescent walls of the external surface of the cathode. This is expressed by:

$$P_1 = \pi d_{ex} \int_0^L \epsilon \sigma T^4(x) dx \quad (2)$$

where $T(x)$ is the temperature of the external surface of the cathode, d_{ex} the outside diameter, L the length of the hot portion of the cathode, ϵ the thermal emissivity of the surface, and σ the Stefan-Boltzmann constant.

2) Thermal conduction in the material of the cathode. This can be evaluated at a point of the tube where there is no energy exchange with the plasma, by using the following equation:

$$P_2 = -\pi e \left(\frac{d_{ex} + d_{in}}{2} \right) k_m(T) \text{ grad } T \quad (3)$$

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where $k_m(T)$ is the thermal conductivity of the cathode material, d_{in} the inside diameter, and e the thickness of the walls of the cathode.

3) Thermal conduction toward the external gas. When the flow of gas injected by the cathode is null, it is given by:

$$P_3 = \pi d_{ex} \int_0^L \phi \, dx \quad (4)$$

where ϕ is equal to [4]:

$$\phi = \frac{K_g(T) (T - T_0)}{\frac{d_{ex}}{2} \ln \left(\frac{D}{d_{ex}} \right) + [\lambda_0(p)] \left[\left(\frac{d_{ex}}{2} \right) + 1 \right]} \quad (5)$$

$K_g(T)$ is the mean value of the conductivity of the gas taken between the two temperatures T and T_0 .

D is the inside diameter of the enclosure, T_0 its temperature, $\lambda_0(p)$ the average free distance of travel of neutral particles at pressure

p , and $\beta^1 = 4.5$ in the case of argon in the presence of a tantalum cathode. According to equation(5) one can note that ϕ is linked to the pressure of the gas by the term $\lambda_\alpha(p)$.

4) Cooling by gas flow: When there exists a gas flow inside the cathode, part of the energy created in the cathodic region is evacuated by the flow. With q being the mass flow of the gas injected by the cathode, T_i and T_f the temperature at the inlet and outlet of the cathode respectively, and C_p the specific heat at constant pressure of the unit of mass circulating in the cathode, the following approximation can be made:

$$P_h = q C_p (T_f - T_i) \quad (6)$$

In reality there is a pressure drop Δp along the cathode and C_p can be attributed to the mean value of the pressure (\bar{p}) in the cathode. At low pressure $\Delta p/\bar{p}$ is high, but as the pressure is increased the ratio of $\Delta p/\bar{p}$ decreases with the ratio becoming

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negligible at atmospheric pressure.

By taking into account the gains and losses given by equations(1) through(6) the balance of energy in the cathodic region can be expressed in the following way:

$$0 = \sum_{i=1}^4 P_i \quad (7)$$

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At low pressure and when thickness e and flow q are low, cooling of the cathodic region is primarily provided by radiation [2] from the external surface of the cathode, and therefore:

$$G \approx P_1 \quad (\text{when } p, q, \text{ and } e \text{ are small}) \quad (8)$$

As flow q and pressure p are increased the two losses P_3 and P_4 take on significance. Figure 3 illustrates the contribution to cooling of the cathodic region that these two elements provide. In this figure we show the longitudinal distribution of temperature on the external surface of the cathode when the discharge is stopped and the cathode is heated by an external means (heating by Joule effect (cf. § 3)). We measured the power supplied to the cathode to heat it to 2000°C in the following two cases:

- 1) At low pressure and zero flow: $p = 10^{-3}$ torr, $Q = 0$
- 2) At high pressure and intense flow: $p = 760$ torr,
 $Q = 30 \text{ cm}^3/\text{sec}$ (TPN).

Although there is a slight shifting of the curve $T(X)$ to the left in the low pressure figure, the general shape of the curve is approximately identical in both cases.

One therefore notes that the power necessary to maintain the cathode at the same temperature varies between 485 W in case 1 and 581 W in case 2, that is, an increase of 96 watts for the entire surface of the cathode: this corresponds to an additional cooling of the cathode through processes P_3 and P_4 of about 24 W/cm^2 . Previous studies [2] revealed that during normal operation of the cathode with a diffused active zone (AZ), the power provided to the internal surface

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	$T_{\text{e}} (^{\circ}\text{C})$	P (torr)	Q ($\text{cm}^3/\text{s TPN}$)	W_{ch} (Watt)
(a)	2000	10^{-3}	0	485
(b)	2000	760	30	581

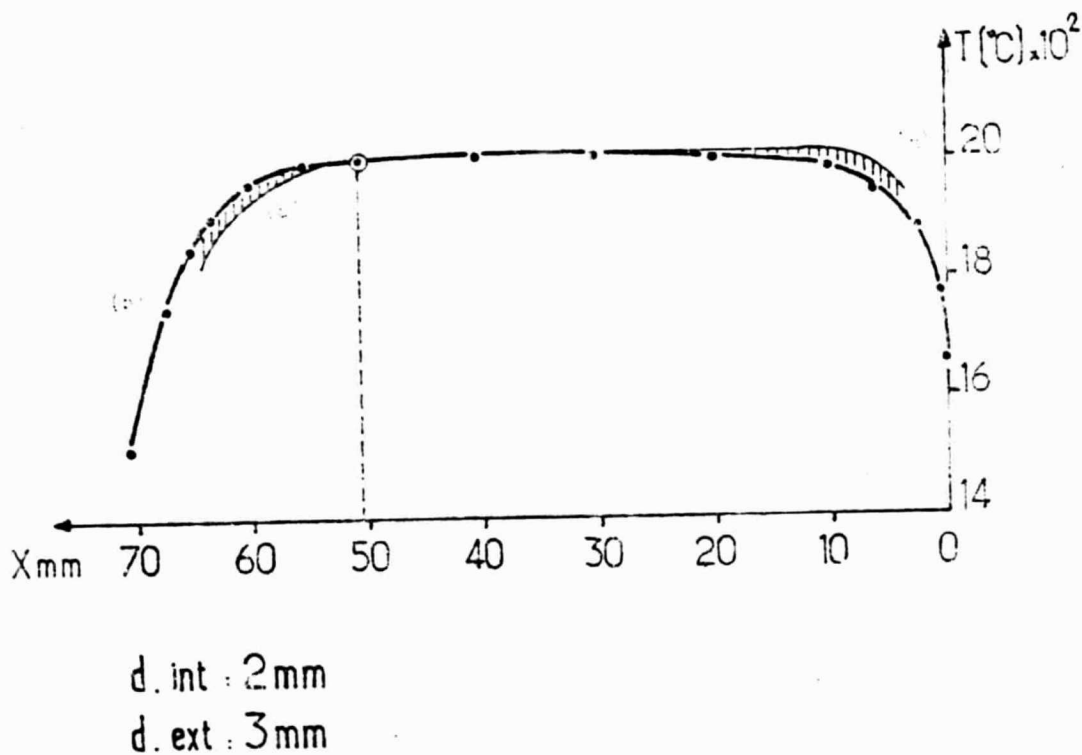


Fig. 3 - Longitudinal distribution of temperature on the external surface of the cathode at two different pressures.

of the cathode by the discharge is in the neighborhood of 50 W/cm^2 , and equation (8) applies. Under these conditions the equilibrium temperature between the gains and the losses near the AZ is about 2500°K , which constitutes optimum operation of the cathode. A large increase in losses by processes P_3 and P_4 would result in a decrease in the mean temperature of the cathode, thus causing either a total halt of the discharge, or a shrinking of the AZ and therefore the appearance of a localized cathodic spot.

3 - METHODS FOR HEATING THE CATHODIC REGION

In order to reduce or compensate for losses P_3 and P_4 we considered the following two solutions:

- a) Either better utilization of the energy created in the cathodic region;
- b) Or additional heating of the cathodic region by a means other than the discharge itself.

Figures 4a and 4b illustrate two variations of method a. In this case the gas flowing in the cathodic region is preheated by the energy G created in this region.

The diagrams illustrating the theory of method b are shown in Figures 4c and 4d. Here the cathode is preheated either by high frequency heating (4c) or by the Joule effect by means of a strong

current flow through the mass of the cathode. The latter method of heating was the one used to obtain the results of the present work.

4 - EXPERIMENTAL RESULTS - DISCUSSION

Figure 5 represents the longitudinal distribution of temperature on the external surface of the cathode at a pressure p of about 100 torr and under the following conditions:

- a) In the presence of a discharge current ($I_D = 3.5$ A) but without preheating of the cathode (curve a).
- b) In the presence of a preheating current ($I_{ch} = 80$ A) but when the discharge is stopped (curve b).
- c) In the presence of discharge and preheating (curve c).

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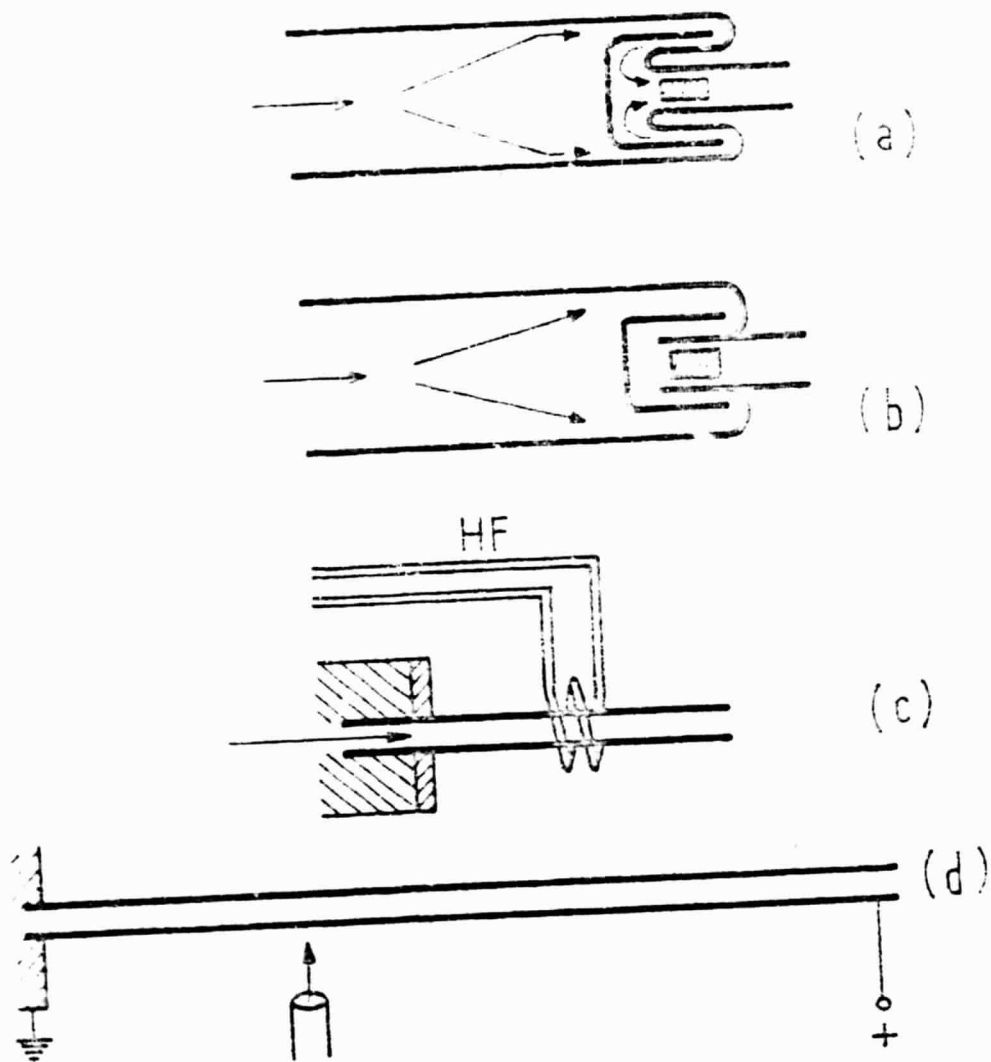


Figure 4 - Various methods of heating the cathodic region.

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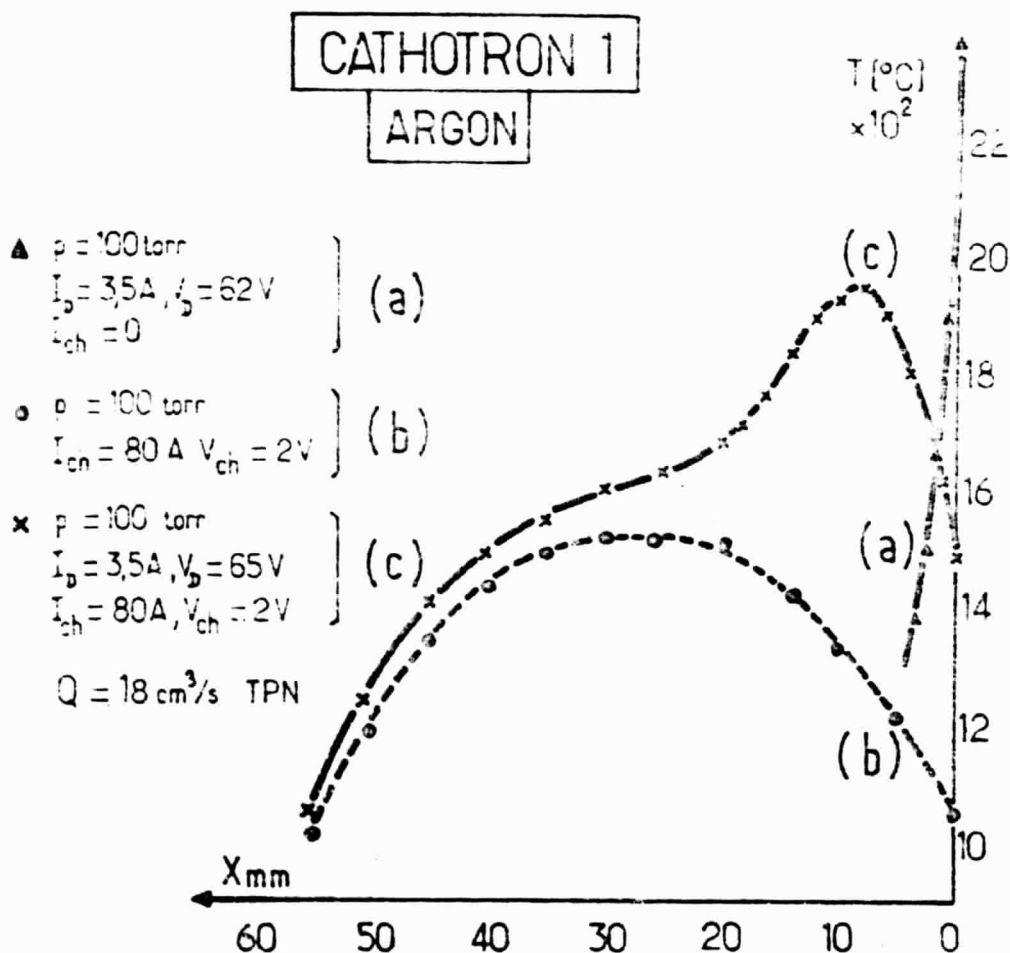


Figure 5 - Longitudinal variations in the temperature of the external surface of the cathode.

One therefore notes that preheating of the cathode results in:

- Increased dimensions of the AZ;
- Favorable decrease in the maximum temperature of the AZ;
- A slight shifting of the AZ toward the inside of the cathode.

The influence of the preheating current (I_{ch}) on the longitudinal distribution of temperature on the cathodic surface $T(X)$ is presented in Figure 6. Note that in this example $p = 760$ torr. These results show that for $I_{ch} > 75$ A the maximum temperature of the AZ is independent of I_{ch} . Also, one notes that when the preheating current is not sufficient to compensate for losses P_3 and P_4 the discharge stops (for $I_{ch} \leq 75$ A).

The influence of the gas flow Q injected by the cathode on $T(x)$ is illustrated in Figure 7. This example clearly shows the influence of loss P_4 on the temperature of the cathode.

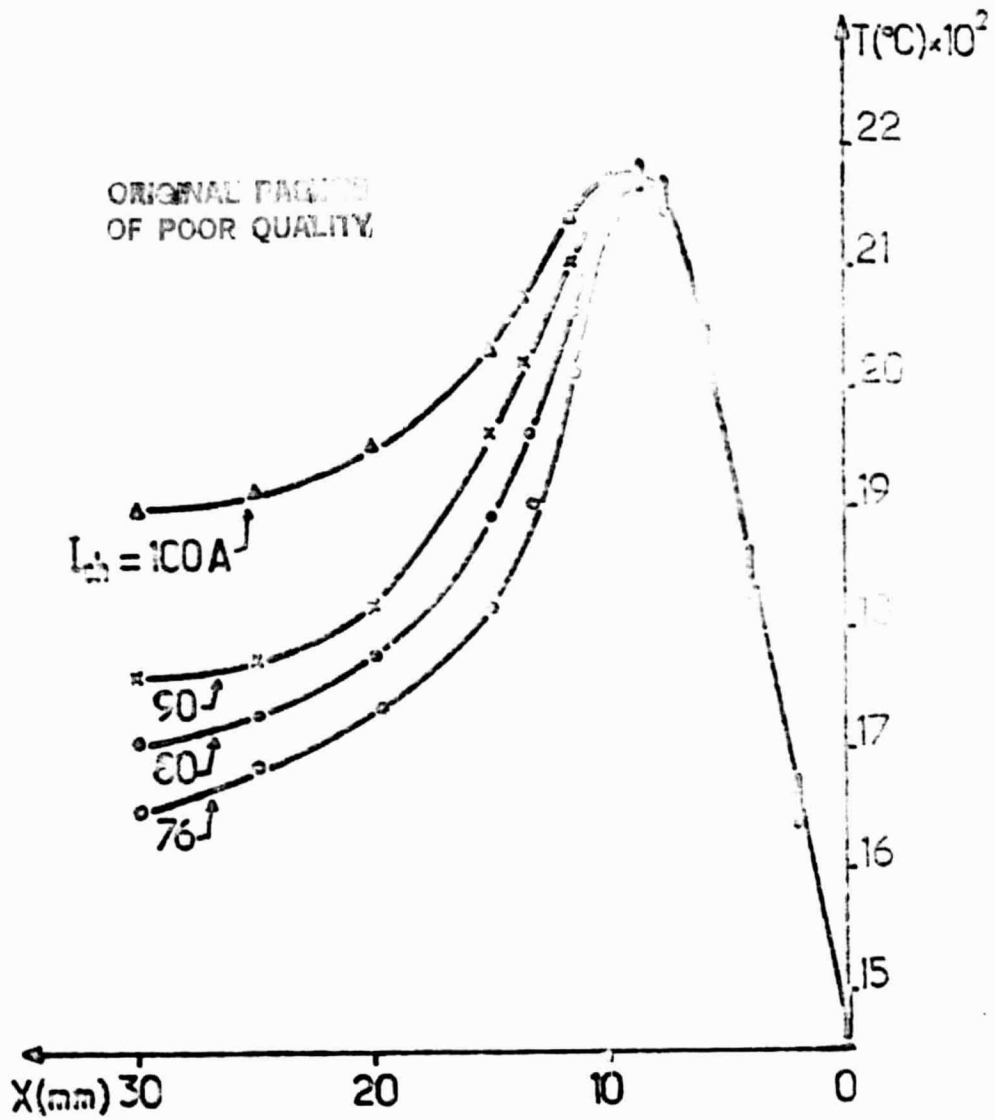
The effect of the discharge current I_D on $T(x)$ is given in Figure 8. One notes that an increase in current I_D results in:

- A shifting of the AZ toward the outlet of the cathode;
- An increase in the temperature of the AZ

Figures 9, 10, and 11 show variations in the discharge voltage V_D as a function of the discharge current I_D , of preheating current I_{ch} and the flow of argon Q injected by the cathodes. These results clearly demonstrate that the discharge voltage varies in such a way as to enable compensation for the variations in losses (P_4) and gains (I_{ch} and I_D).

Also, the linear variation of V_D as a function of Q in Figure 10 suggests that the temperature of the gas at the outlet of the cathode is independent of flow Q .

Indeed, V_D represents the power per unit of current supplied upon discharge, and since p and I_D remain constant and the anode and plasma regions external to the cathode are independent of Q , one can assume that the increase in V_D is connected with increases in loss P_4 in the cathodic region. By combining



$p = 760 \text{ torr}$	$Q = 28 \text{ cmc/s TPN}$				
$I_{ch} \text{ (Amp)}$	75	76	80	90	100
$I_p \text{ (Amp)}$	0		3		

Figure 6 - Influence of the preheating current I_{ch} on the longitudinal distribution of temperature on the cathodic surface.

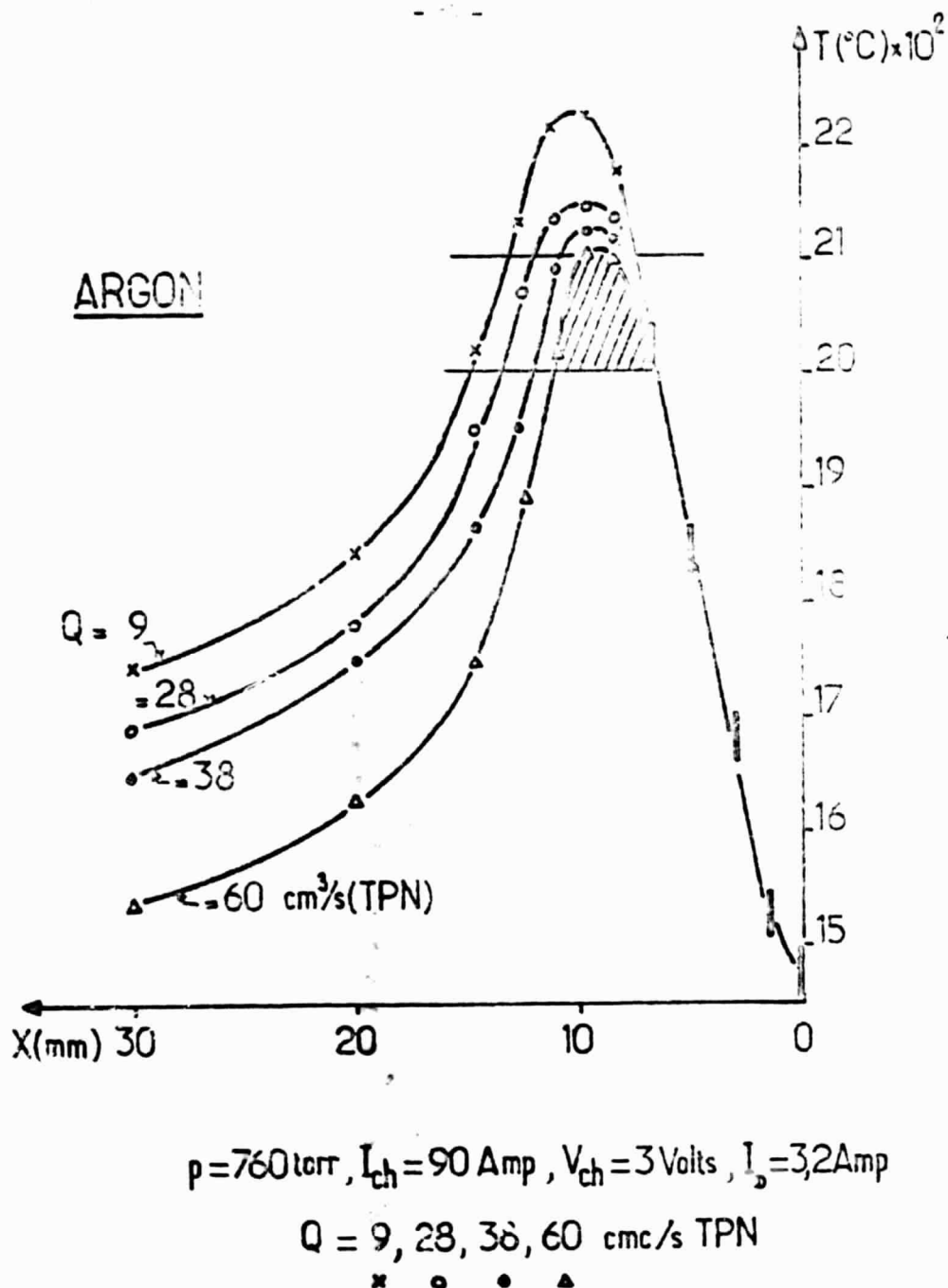
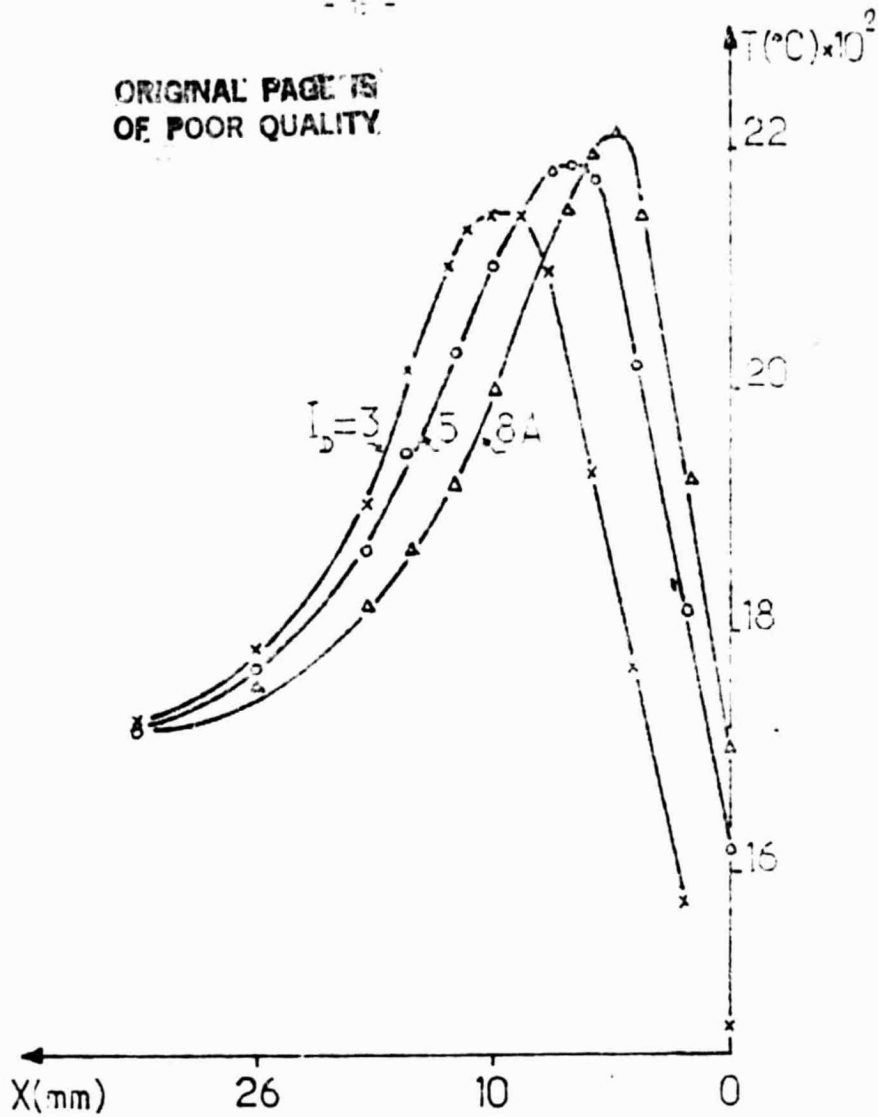


Figure 7 - Influence of the gas flow Q injected by the cathode on the longitudinal distribution of temperature $T(x)$.



$p = 760 \text{ torr}, I_{ch} = 90 \text{ Amp}, V_{ch} = 3 \text{ Volts}, Q = 28 \text{ cmc/s TPN}$

$I_D = 3, 5, 8 \text{ Amp}$
 $\quad \quad \quad x \quad o \quad \Delta$

Figure 8 - Effect of discharge current I_D on $T(x)$.

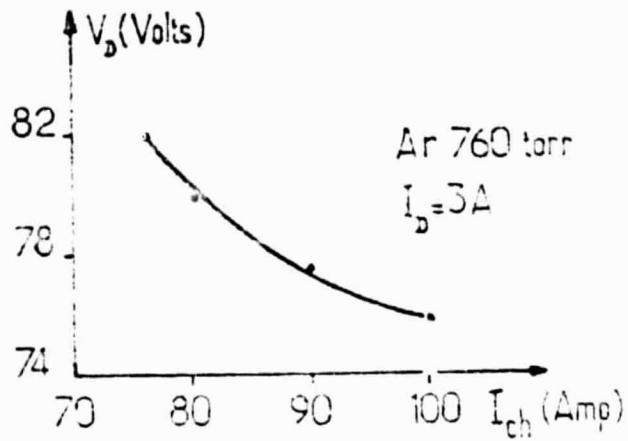


Figure 9 - Variations in discharge voltage V_D as a function of preheating current I_{ch} .

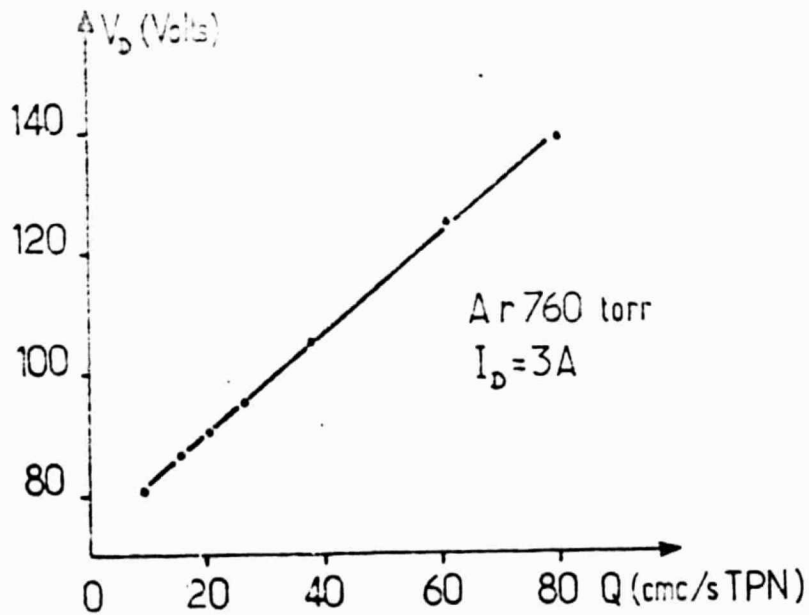


Figure 10 - Variations in V_D as a function of flow Q .

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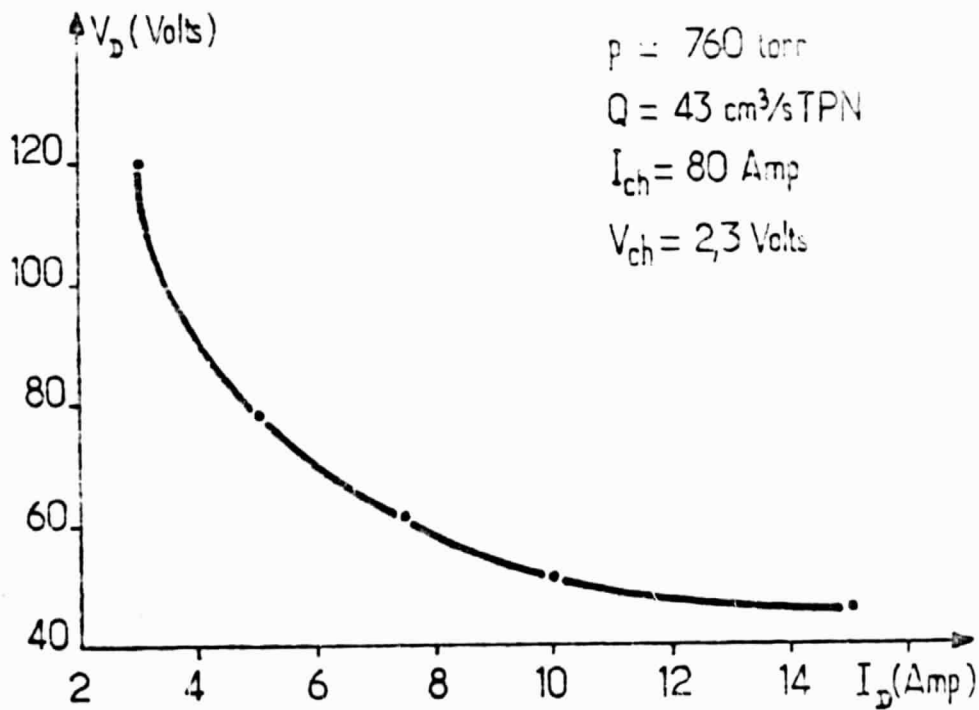


Figure 11 - Variations in discharge voltage V_D as a function of discharge current I_D .

the results of Figure 10 and equation 6 the following statement can be written:

$$\frac{p_b}{q} = C_m (T_f - T_i) = \text{a constant} \quad (9)$$

and since C_m and T_i do not change we can conclude that T_f is constant and independent of the flow.

Lastly, Figure 12 shows the variations of V_D as a function of pressure p in the enclosure and for different gases.

These results motivated us to devise various types of experimental setups called cathotrons 1, 2, and 3 which we will now describe in brief:

Cathotron 1 is shown in Figure 13. The numbers in this figure refer to the following:

- 1 - Cathodic cavity (Ta)
- 2 - Plate made of Ta
- 3 - External cylinder made of Ta
- 4 - Electrical insulator
- 5 - Water-cooled cathode mount

Cathotron 2 is a variant of cathotron 1 which enables the use of any gas (either chemically active or not) (cf. Fig. 14).

The above two variations of cathotrons are in keeping with the classical cathode-anode setup and the plasma is located between the two electrodes.

Cathotron 3 is a variant in which the two electrodes are assembled in a similar way to that of the plasmatron device. Figure 15 shows a simplified diagram of this device.

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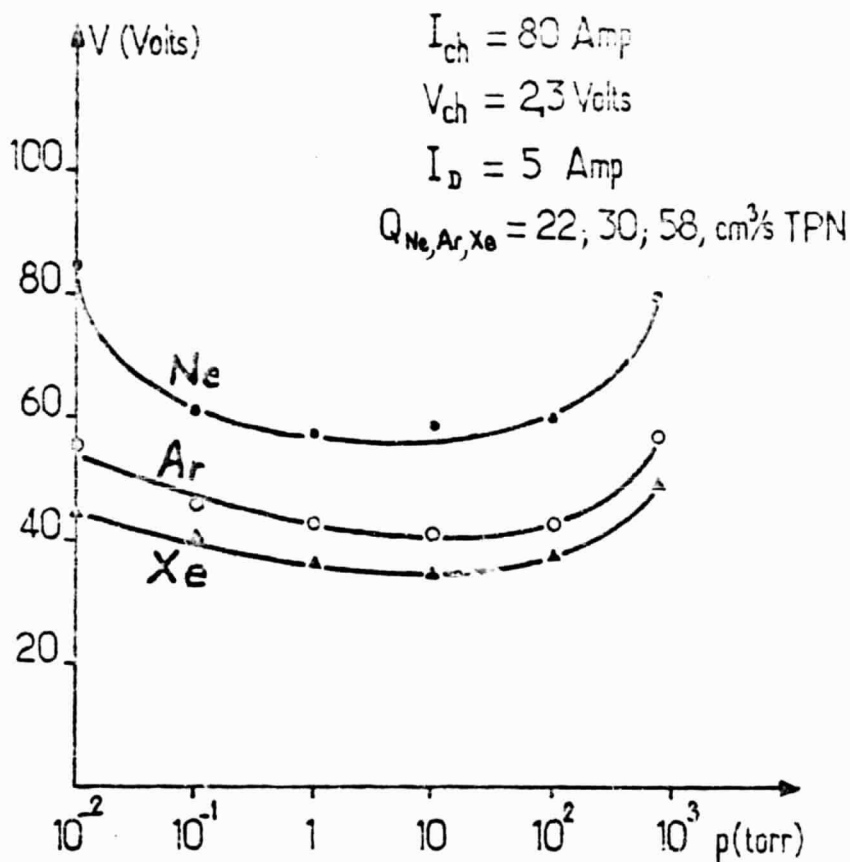


Figure 12 - Variations in discharge voltage V_D as a function of the pressure p in the enclosure.

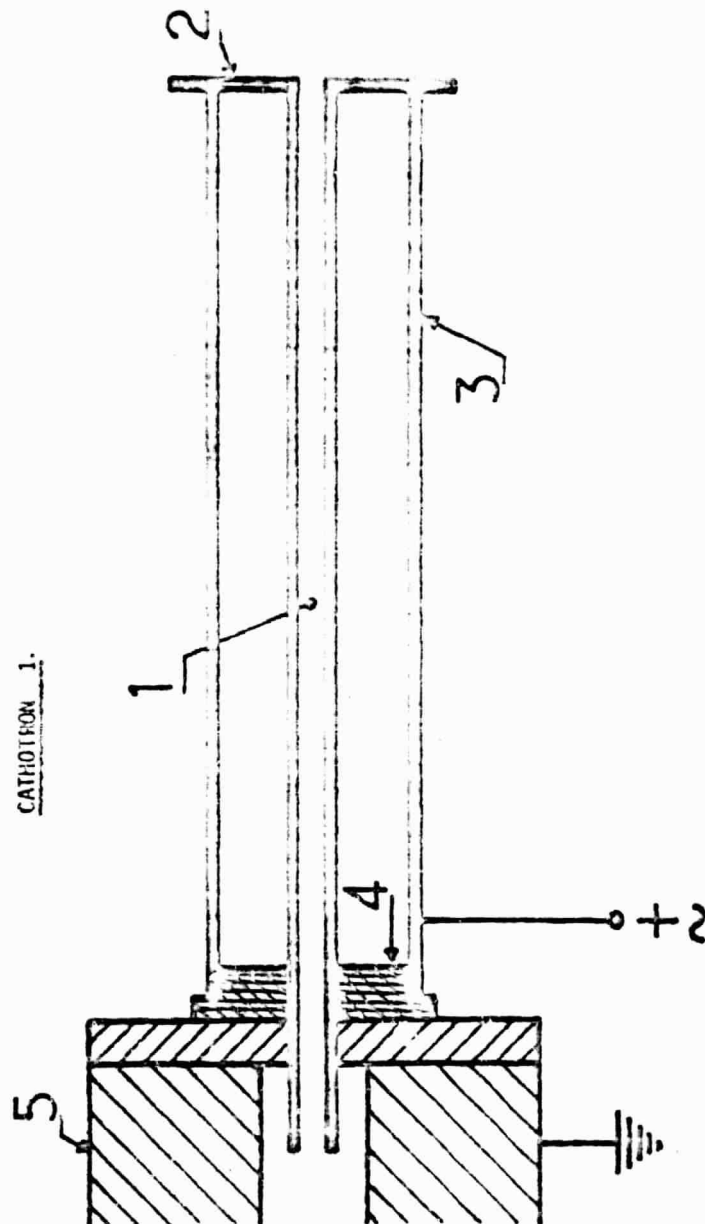


Figure 13

CATHOTRON 2.

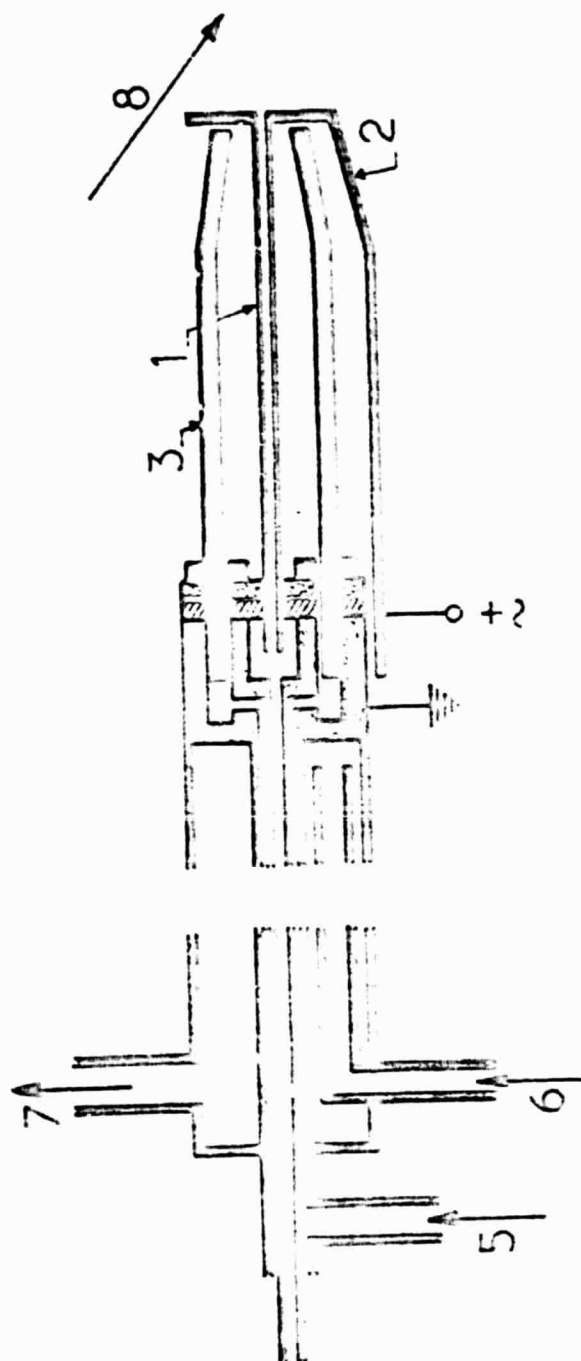
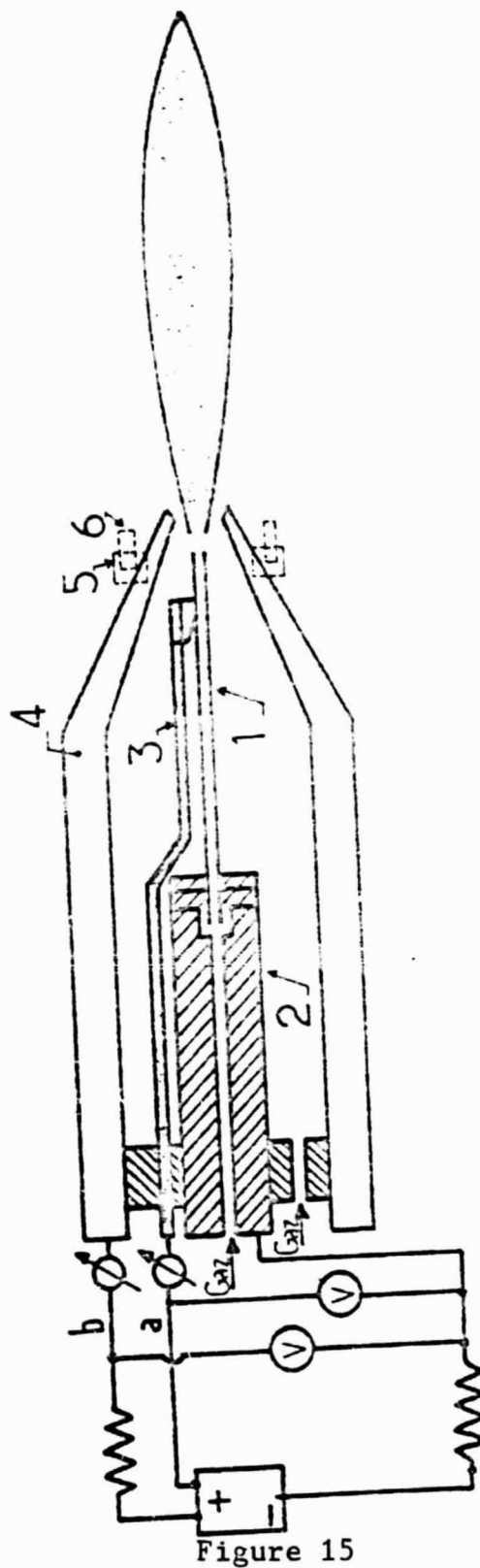


Figure 14

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CATHODE 3.



- 1 Cathode
- 2 Cooled mount
- 3 Conductor
- 4 Anode
- 5 Initiation system
- 6 Focusing system

APPENDIX A - EXPERIMENTAL SYSTEM

HEATING METHODS

1 - INTRODUCTION

The results obtained at the Laboratory of Plasma Physics of the Orsay Sciences Faculty demonstrated that a hollow-cathode gas-flow arc discharge has led to interesting prospects for MHD generators.

Indeed, the high discharge current levels ($1.5 \leq I \leq 300$ A for a simple cathode, and $2 \leq I \leq 500$ A for a multiple-channel cathode), the low cathodic drops (about 10 V) in the presence of diffused operation of the cathodic spot, and a cathode life of about 10 hours for a simple cathode and more than 100 hours for a multiple-channel cathode, justify these prospects.

The preliminary experiments performed under conditions neighboring those of MHD generators show the changes in cathodic discharge operation at pressures in the vicinity of one atmosphere which, with a slight increase in the temperature, consist in a shrinking and

shifting of the incandescent part of the cathode (called the "active zone") toward the end of the cathode. In this way an excess of thermal activity on the cathode is produced, greatly reducing the life of the cathode in the higher-pressure range.

The research project within the scope of the present contract consists in studying the behavior of hollow gas-flow cathodes under conditions similar to those of MHD generators.

This study is concerned with the determination of an operating range of multiple-channel hollow cathodes at near-atmospheric pressure with higher current densities and reduced gas flows in the presence of a longitudinal magnetic field.

2 - EXPERIMENTAL SYSTEM - HEATING METHODS

Analysis of the energy dissipated by metal and metal/gas conductivity, as well as radiation, shows that increasing the pressure to levels near one atmosphere gives rise to considerable redistribution of the energy dissipated in the region of the cathode.

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While the losses due to radiation only depend on the temperature of the metal and the cathode, the losses due to metal-gas conduction are dependent upon the pressure and will therefore be much greater at atmospheric pressure than at pressures in the vicinity of 10^{-2} torr.

In order to improve the energy balance we adopted as a work hypothesis, and as part of the contract, the possibility of compensating for the losses due to metal-gas conductivity by additionally heating the gas injected by the cathode and the cathode itself.

An increase in the discharge current and a decrease in the cathodic drop - conditions which are also necessary for the operation of an MHD generator - can be effected by increasing the emissive surface of the cathode in the effective region of the discharge.

As the second part of the work hypothesis we opted for modification of the volt-ampere characteristic of the discharge by enlargement of the emissive surface through additional heating of the cathode to temperatures corresponding to a large thermoelectric emission.

We developed two methods of heating the gas injected by the cathode (by conductivity and radiation), represented in Figures 2a and 2b, and two methods of direct heating of the cathode (by high frequency and Joule effect), represented in Figures 2c and 2d.

In the case of a, heating of the gas injected by cathode C_2 of the primary discharge C_2-A_2 is performed by heating the tube through which the gas arrives by means of auxiliary discharge C_1-A_1 .

Heating of the gas in process b is done by direct contact of the gas with the incandescent external surface, which constitutes the active zone of the cathode, before being injected into the cathode. This

method enables the cathode losses due to metal-gas conductivity and radiation to be used to initially heat the injected gas.

Parts c and d of Figure 2 give a schematic representation of the possibilities for heating the cathodes by high frequency and Joule effect.

Figure 1 shows the general diagram of our installation; the system was designed so that we could easily switch from one heating method to another while maintaining the same experimental conditions. In this way it is possible to compare the results obtained as well as their effectiveness.

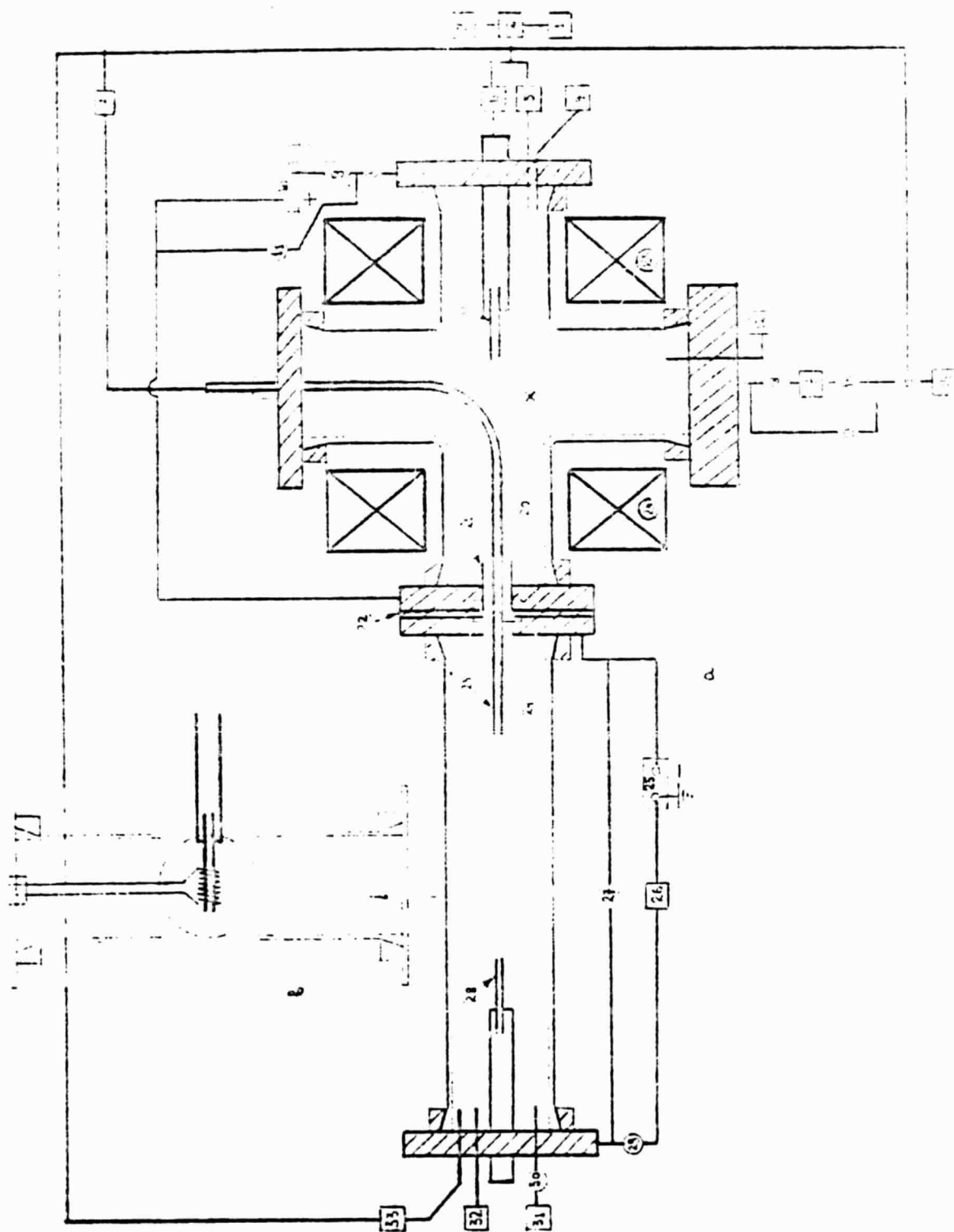


Figure 1 - General diagram of installation.

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FIGURE 1GENERAL DIAGRAM OF INSTALLATION

- An enclosure (20) made of glass with 6 arms (two perpendicular to the surface of Figure 1a shown separately on cross section b) for determining the influence of additional heating by:
 - conductivity and radiation of the gas injected by the cathode;
 - Joule effect and high frequency to heat the cathode and the gas that it injects

on the cathodic (13) and anodic (21) discharge.
- An enclosure (2) made of glass containing argon at atmospheric pressure linked to enclosure 20 which contains argon at low pressure. They are used to determine the effect of heating the cathode- (22) injected gas by conductivity and radiation, on the cathodic (23) and anodic (28) primary discharge by using the plasma of the auxiliary discharge (13) - (21).
- Vacuum system (12, 18, 17, 16, 19, 15, 14, 30, 31)
- Argon supply system (1 - 7, 32, 33)
- Magnetic field coils (23, 24)
- Electrical supply system (8 - 11, 25 - 27, 29)

VARIOUS COMPONENTS

Argon tank	(1)	Pirani gage	(12)
Buffer chamber	(2)	Cathodes	(13)(23)
Pressure gages	(3)(4)(32)	Primary pumps	(14)(31)
Flowmeters	(5-7)(23)	Valves	(15)(16)(18)
Ammeters	(8)(29)		(19)(30)
Potentiometers	(9)(26)	Secondary pumps	(17)
Electric generators	(10)(25)	Enclosures	(20)(24)
Voltmeters	(11)(27)	Insulator	(22)
		Magnetic field coils	(23)(24)

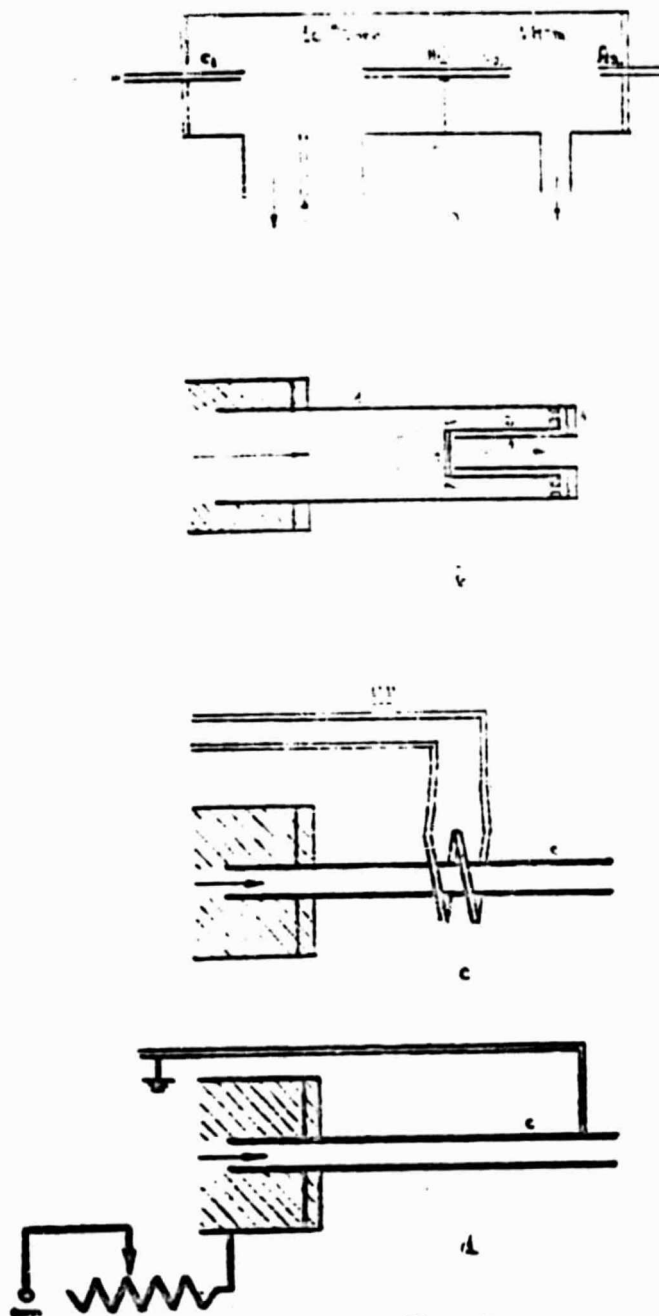


Fig. 2

Figure 2 - Various methods of heating the cathode.

3 - CONCLUSIONS

Analysis of the hollow gas-flow cathode discharge mechanism enables one to assume that the cathodic heating methods developed as part of this contract will be effective in obtaining a discharge operation that is in accordance with the operation of MHD generators.

Preliminary heating of the gas injected by the cathode brings about a decrease in the loss due to metal-gas conductivity. Direct heating of the cathode brings about a radical change in the energy balance of the discharge by causing a considerable increase in the amount of current flow and a decrease in the cathodic drop.

In addition, direct heating of the cathode makes it possible to use simple cathodes and multiple-channel cathodes of greater thickness, thus ensuring a longer service life.

As a general rule the additional cathodic heating that has been suggested will enable a considerable improvement in the performance of the hollow gas-flow cathode arc discharge. Furthermore, the use of these discharges with cathodic heating will be applicable in the following fields:

- Construction of stable plasma columns through charge exchange
- Electron sources
- Ion lasers
- Electrochemical synthesis and dissociation

APPENDIX P

END-OF-CONTRACT REPORT - SCIENTIFIC PUBLICATIONS

Activities organized by "Electronique Nouvelle"

Contract No.: 69.01.792

Official Agency: D.G.R.S.T. (Delegation Generale a la Recherche Scientifique et Technique = General Delegation for Scientific and Technical Research)

Contracting laboratory: Laboratory of Plasma Physics

University of Paris XI - Orsay Center

91405 Orsay

Title: Gas-flow arc electrodes

J. L. Delcroix - H. Minoo - C. Popovici: High pressure operation of hollow cathode arc discharges (Cathotrons). Conference on hollow-cathode discharges and their applications (Orsay, Sept. 1971). Contributed papers, p. 18.